The EUV airglow of Titan: Production and loss of $N_2 \, c'_4(0) - X$

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Abstract. The N_2 Carroll-Yoshino (CY) $c'_4 - X$ (0,0) and (0,1) Rydberg bands between 95 and 99 nm were reported to be the most prominent EUV emission features in Voyager 1 ultraviolet spectrometer (UVS) airglow spectra from Titan's atmosphere. Although c'_4 is strongly excited by photoelectron impact, the (0,0) band is optically thick near peak production, so a multiple-scattering model is employed to calculate $(0, v'')$ nadir-viewing intensities. The model accounts for all known loss processes and quantifies the redistribution of photons to $(0, v'' > 0)$. Results show 7.6 R of (0,1) intensity, in agreement with reported observations (5–10 R), and 0.2 R of (0,0), in spectacular disagreement with reported observations (6–10 R). Nadir-viewing intensities of all other expected NI multiplets and N_2 bands in the brightest portion of the EUV airglow spectrum (92.0–101.5 nm) are also calculated using photodissociative ionization of N_2 and photoelectron impact on N_2. It is found that NI multiplets and N_2 bands near (0,0) and unresolved by the UVS combine to produce 8.3 R, consistent with that reported for (0,0) and indicating that it was misidentified in previous analyses. The Ultraviolet Imaging Spectrograph (UVIS) on Cassini should unambiguously distinguish any (0,0) intensity from the brightest features nearby.

1. Introduction

Analyses of Voyager 1 ultraviolet spectrometer (UVS) airglow data from Titan argued that the spectrum between 54 and 120 nm is dominated by the N_2 Carroll-Yoshino (CY) $c'^{1}_4\Sigma^+_u - X^1\Sigma^+_g$ (0,0) and (0,1) Rydberg bands near 95.86 and 98.05 nm, respectively [*Broadfoot et al.*, 1981; *Strobel and Shemansky*, 1982; *Hall et al.*, 1992]. Although these bands are excited by photoelectron impact, the resonant (0,0) band is extremely optically thick to self-absorption near peak production, thereby trapping the radiation internally and ruling out significant (0,0) emission observable from outside the atmosphere. This means that photoelectrons are not important in exciting the N_2 airglow on Titan and/or the analysis of the UVS spectral content is more complicated than previously believed.

Photoelectron excitation of $c'_4(0)$ is followed by multiple scatterings of emitted photons which eventually either branch to more optically thin bands ($v'' > 0$) or are lost to predissociation. Predissociation has not been included in previous airglow models on Titan owing primarily to the lack of a reliable $c'_4(0)$ yield [*Strobel and Shemansky*, 1982; *Strobel et al.*, 1991; *Gan et al.*, 1992; *Strobel et al.*, 1992]. Recently, however, *Shemansky et al.* [1995] inferred a predissociation yield of 0.125 for the inferred temperatures at Titan, and *Stevens et al.* [1994] found that multiple scatterings of (0,0) enhance $(0, v'')$ loss by predissociation to 3 times the optically thin yield in the Earth's atmosphere. This suggests a significant overestimate of emergent $(0, v'')$ intensity in previous Titan airglow models.

Solar photons with wavelengths <45 nm initiate photoelectron excitation of $c'_4(0)$. Titan EUV airglow models using the solar spectral atlas of *Hinteregger et al.* [1981] (hereinafter referred to as SC21REFW) required additional excitation to explain the observations [*Strobel et al.*, 1991, 1992]. Comparisons with other solar EUV models and measurements [*Richards et al.*, 1994; *Warren et al.*, 1998] showed that the SC21REFW photon flux is consistently low by about a factor of 2, leading to an underestimate of $(0, v'')$ produced from photoelectrons in Titan's atmosphere.

The purpose of this work is to calculate the distribution of nadir-viewing intensities between 92.0 and 101.5 nm, the brightest portion of the EUV observed by the UVS. A comprehensive multiple-scattering algorithm is used for the $CY(0, v'')$ bands that includes self-absorption, predissociation, redistribution to $v'' > 0$, and extinction. The calculation of all other N_2 bands and NI multiplets assumes excitation by both photoelectrons on N_2 and photodissociative ionization of N_2. This is the first study to quantify the contribution of NI emission to Titan's airglow between 92.0 and 101.5 nm. A solar spectrum that is about a factor of 2 brighter in the EUV than SC21REFW is used to calculate production rates. Results from the model are compared to reported UVS observations, and a predicted Titan EUV airglow spectrum is provided for use in the analysis of future observations by the Ultraviolet Imaging Spectrograph (UVIS) on Cassini.
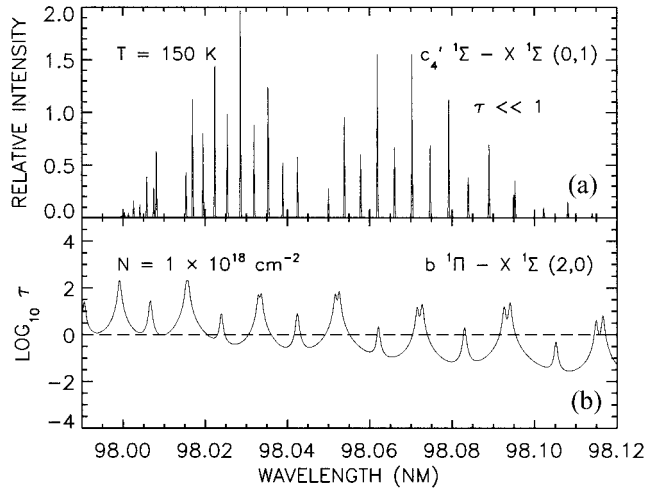
2. Procedure

Stevens et al. [1994] synthesized the rotational lines of CY(0,0) and (0,1) and calculated the fate of line radiation through the Earth's atmosphere over multiple scatterings by including all known loss processes. An important effect that had not been quantified before was branching to (0,1), followed by absorption in the Birge-Hopfield (BH I) $b^1\Pi_u - X^1\Sigma^+_g$ (2,0) band of N_2 near 98 nm, which accidentally overlaps CY(0,1). Since BH I(2,0) is 100% predissociated, this accidental resonance leads to photon loss. Stevens et al. showed that most $CY(0, v'')$ intensity appears in (0,1), consistent with terrestrial observations [*Morrison et al.*, 1990], and explained the apparent discrepancy between the large $c'_4(0)$ excitation rate and the weak $(0, v'')$ intensity observed from the Earth's atmosphere. Details of the model are given by Stevens et al.

Report Documentation Page

1. REPORT DATE **MAR 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **The EUV airglow of Titan: Production and loss of N2 c'4(0) - X**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT **see report**

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Figure 1. (a) The CY(0,1) band modeled at 150 K. (b) Modeled BH I(2,0) optical depths at 150 K. Optical depths are calculated for the N_2 column abundance shown, which is near peak photoelectron production on Titan. The band origin is at 97.88 nm.

The multiple-scattering model developed for the Earth's atmosphere is employed herein to model the CY$(0, v'')$ intensities from Titan's N_2 atmosphere. The loss processes included are the same except that O_2 extinction in the Earth's atmosphere is replaced by methane (CH_4) extinction on Titan. The model atmosphere, the solar EUV and X-ray irradiances, the $c'_4(0)$ excitation rates, and the branching ratios from $c'_4(0)$ are all required input.

A model atmosphere consistent with the revised analysis of the Voyager 1 UVS ingress occultation reported by R. J. Vervack et al. (First results from a reanalysis of the Voyager 1 Ultraviolet Spectrometer solar occultations by Titan, submitted to *Icarus*, 2000) is used in this study, where the CH_4 mixing ratio is constant at 1.6% in the upper atmosphere (600–1500 km) and the temperature is isothermal at 150 K. Figures 1a and 1b show the modeled rotational structure of the CY(0,1) and BH I(2,0) bands at 150 K. Note that the $X(1)$ vibrational level is assumed to be in thermal equilibrium, which makes (0,1) optically thin to self-absorption at all altitudes of this work. BH I(2,0) optical depths in Figure 1b are calculated using a column abundance of 1×10^{18} cm^{-2}, consistent with the N_2 vertical column near peak photoelectron production. At 150 K, populations for both bands peak in the lowest rotational levels, minimizing their overlap and increasing the survival rate of (0,1) photons compared to Earth.

The solar EUV photon flux between 5 and 45 nm and especially the X-ray flux below 5 nm are currently areas where discrepancies of a factor of 2 or more exist between different models and measurements under quiet Sun conditions [*Richards et al.*, 1994; *Warren et al.*, 1998]. This study uses the solar spectrum observed by *Woods et al.* [1998] (hereinafter referred to as NCAR/CU) to calculate all production rates. The Voyager 1 encounter with Titan occurred near solar maximum ($F_{10.7} = 256 \times 10^{-22}$ W cm^{-2} Hz^{-1}), and the NCAR/CU quiet Sun spectrum is adjusted to Voyager 1 conditions using the *Hinteregger et al.* [1981] scaling algorithm. The spectrum is shown in Table 1 for quiet and active Sun conditions at 1 AU. Under quiet Sun conditions the total NCAR/CU energy flux shown in Table 1 is a factor of 1.7 larger than SC21REFW, and under active Sun conditions it is larger by a factor of 2.5.

The production rate $P(z)$ of $c'_4(0)$ is given by

$$P(z) = n(z) \int \sigma(E) \varphi(z, E) \, dE, \qquad (1)$$

where $n(z)$ is the local N_2 number density (in cm^{-3}), $\sigma(E)$ is the excitation cross section (in cm^2), and $\varphi(z, E)$ is the photoelectron flux (in cm^{-2} s^{-1} eV^{-1}) at altitude z and electron energy E. To calculate excitation cross sections, $(0, v'')$ emission cross sections of *Ajello et al.* [1989] were scaled up, accounting for the loss due to predissociation [*Shemansky et al.*, 1995; *Ubachs*, 1997] and Gaydon-Herman (GH) $c'_4\,^1\Sigma_u^+ - a\,^1\Pi_g(0, v'')$ emission [*Filippelli et al.*, 1984] shown in Table 2. The $c'_4(0)$ excitation cross section at 100 eV is therefore calculated to be 1.02×10^{-17} cm^2. Photoelectron fluxes are calculated for the Earth's atmosphere with the Atmospheric Ultraviolet Radiance Integrated Code [*Strickland et al.*, 1999], without O_2 and atomic oxygen. Calculated production rates are reduced by $1/R^2$ ($R = 9.539$ AU) and mapped to Titan's atmosphere using the N_2 column abundance to the Sun following the procedure of *Strobel et al.* [1992]. Production rates as a function of altitude for $c'_4(0)$ at Titan are shown in Figure 2.

Table 1. Solar EUV and X-Ray Fluxes[a]

| λ, nm | Quiet Sun ($F_{10.7} = 85.9$) | | Active Sun ($F_{10.7} = 256$) | |
	Photon Flux, 10^9 cm^{-2} s^{-1}	Energy Flux, erg cm^{-2} s^{-1}	Photon Flux, 10^9 cm^{-2} s^{-1}	Energy Flux, erg cm^{-2} s^{-1}
1.1–2	0.007	0.010	0.178	0.232
2–5	0.128	0.064	1.109	0.607
5–10	1.066	0.293	3.726	1.035
10–15	0.46	0.076	1.32	0.207
15–20	3.34	0.372	11.51	1.265
20–25	1.74	0.153	9.27	0.828
25.632	0.43	0.034	0.67	0.052
28.415	0.31	0.022	12.76	0.892
25–30	1.63	0.120	10.90	0.810
30.331	0.22	0.014	2.76	0.181
30.378	3.08	0.201	5.47	0.358
30–35	4.58	0.273	36.01	2.149
36.807	0.26	0.014	0.54	0.029
35–40	1.93	0.107	24.64	1.356
40–45	1.04	0.050	2.99	0.142
Total	20.23	1.80	123.9	10.14

[a] All fluxes at 1 AU and fluxes in band regions do not include contributions from lines listed. Line fluxes from *Warren et al.* [1998]. Quiet Sun photon fluxes <2 nm are SC21REFW fluxes scaled to NCAR/CU as the 2–5 nm photon flux. Active Sun conditions are for Voyager 1 UVS observations on November 11, 1980.

Table 2. Branching From $c'_4(0)$ at 150 K

| Transition From $c'_4(0)$	Branching Ratio
$X(0)$	0.728
$X(1)$	0.125
Predissociation	0.120
$X(2)$	0.011
$X(v'' > 2)$	0.010
$a\,^1\Pi_g$	0.008
Total	1.00

3. Radiative Transfer of CY(0,v'')

The vertical optical depth of the strongest CY(0,0) rotational lines near peak production is found to be in excess of 10^4 and prevents observation of (0,0) emission originating from below the exobase. The most important loss processes are shown in Figure 3 for the production in Figure 2 and the branching ratios in Table 2. In general, ~10 scatterings are required to deplete the $c_4'(0)$ production by 90%. Multiple scatterings enhance the likelihood of predissociation from 12.5% (optically thin value) to 41%, roughly consistent with the terrestrial case [*Stevens et al.*, 1994]. Other important loss processes in Figure 3 are BH I(2,0) absorption of CY(0,1) (18% probability) and CH_4 extinction of CY(0,1) (14%). The altitude of vertical optical depth unity for CY(0,1) is included in Figure 3. The $\tau_{0-1} = 1$ level is not well defined because of the complex rotational structure of the overlapping BH I(2,0) band (Figure 1) and is included only as a guide. The estimate uses an average N_2 cross section of 1×10^{-18} cm^2 and a CH_4 absorption cross section at 98 nm of 4.0×10^{-17} cm^2 [*Au et al.*, 1993].

4. Other EUV Emission: 92.0–101.5 nm

Samson et al. [1991] found that NI multiplets near 95.32 and 96.45 nm as well as NII 91.6, NII 108.5 nm, and a variety of other NII and NI multiplets are produced from photodissociative ionization of N_2 through the unbound N_2^+ $H^2\Sigma_g^+$ state. *Meier et al.* [1991] calculated the cross section for production of N_2^+(H) by the solar EUV and X-ray irradiance as well as yields for the resultant NI and NII multiplets in the Earth's atmosphere. They found that NII 108.5 nm production by photodissociative ionization is over an order of magnitude larger than by photoelectron production. *Strobel et al.* [1991, 1992] used the cross sections and yields of Meier et al. To calculate NII 91.6 and NII 108.5 nm emission rates in Titan's atmosphere and found that production by photodissociative ionization is similarly many times more important than by photoelectrons.

In the present work the cross sections of *Meier et al.* [1991]
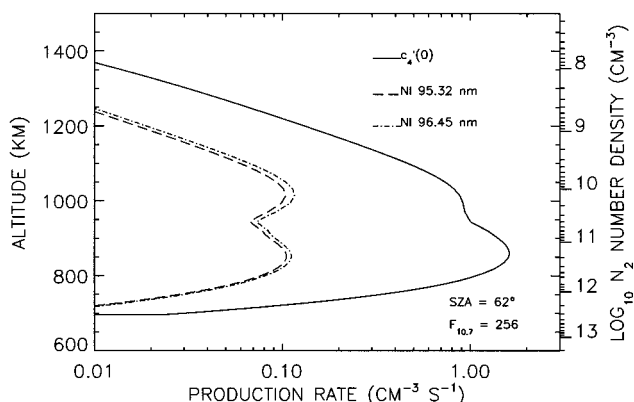
Figure 2. The calculated $c_4'(0)$ and NI 95.32 and 96.45 nm production for Voyager 1 conditions. The NI multiplets include contributions from both photodissociative ionization and photoelectrons. The total altitude integrated production is 40.2 R for $c_4'(0)$, 3.8 R for NI 96.45 nm, and 3.5 R for NI 95.32 nm. The solar zenith angle (SZA) and the $F_{10.7}$ flux used in the calculation are shown, and the local N_2 number density for the model atmosphere used is on the right-hand axis.
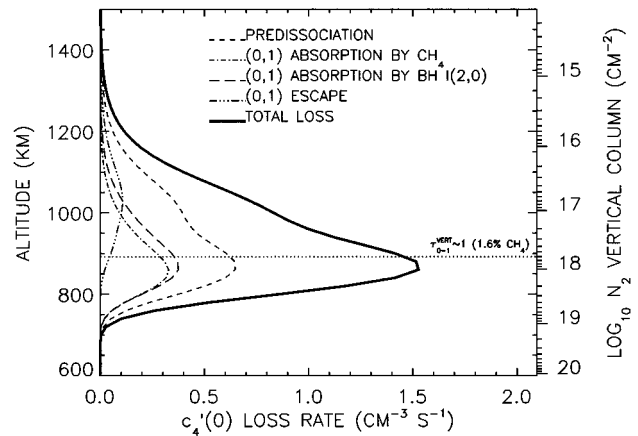
Figure 3. The most important loss processes calculated using the $c_4'(0)$ photoelectron production rate shown in Figure 2.

are convolved with the solar spectrum in Table 1 and the total N_2 absorption cross sections of *Kirby et al.* [1979] to calculate NI 95.32 and 96.45 nm photodissociative ionization production rates as a function of altitude at Titan. The calculation of NI 95.32 and 96.45 nm photoelectron production uses cross sections at 100 eV of 4.4×10^{-19} cm^2 and 4.3×10^{-19} cm^2, respectively [*Ajello et al.*, 1989, 1998], and the energy dependence of NI 119.99 nm measured by *Ajello and Shemansky* [1985] normalized so that the threshold potential is consistent with the higher-energy transitions. The total production rates of NI 95.32 and 96.45 nm as a function of altitude are shown in Figure 2. The contribution from photoelectrons (~25%) is heavily weighted to the lower peak, where the emission is more optically thick to CH_4. Note that at a spectral resolution of ~3.3 nm, these two multiplets will appear as a single feature near CY(0,0) at 95.86 nm in the UVS data.

Photoelectron production rates for other N_2 bands and for NII 108.5 are calculated using (1) along with the emission cross sections and predissociation yields of *Ajello et al.* [1998], *Ajello et al.* [1989], and *James et al.* [1990]. The N_2 bands included in addition to CY(0,v'') are CY(3,v''), CY(4,v''), CY(6,v''), $b'(9,v'')$, $b'(16,v'')$, and $b(1,v'')$. The $b(1,0)$ band near 98.6 nm is found to be optically thick and is not included here [*Stark et al.*, 1992; *Feldman et al.*, 2001]. Redistribution of photons within all other bands is much less than for CY(0,v'') and is not calculated here because either the resonant (v',0) branching ratio is small or the predissociation yield of the excited state is large, inhibiting multiple scattering.

5. Results

Calculated CY(0,v'') nadir-viewing intensities from the excitation shown in Figure 2 are listed in Table 3 along with contributions from the other emission features where CH_4 extinction is included; the brightest are listed first. For reference, the total intensity of the prominent NII 108.5 multiplet is included and found to be 15.0 R, consistent with previous UVS spectral analyses yielding 12–24 R [*Strobel and Shemansky*, 1982; *Hall et al.*, 1992]. The NII 91.6 nm multiplet is calculated to be much weaker, so that comparisons with the inferred UVS intensity are not instructive [*Strobel et al.*, 1992]. Totals in Table 3 show that the CY(0,$v'' = 0,1,2$) intensities are less than half of all the intensity between 92.0 and 101.5 nm.

Table 3. Model EUV Intensities

Emission Feature	λ, nm	Nadir Intensity,[a] R
NII	108.5	15.0 (13.2)[b]
CY(0,1)	98.05	7.6
NI	96.45	2.8 (2.4)[b]
NI	95.32	2.6 (2.1)[b]
CY(0,2)	100.31	1.0
CY(4,3)	94.46	0.8
CY(4,5)	98.61	0.6
b(1,1)	100.88	0.6
CY(3,2)	94.32	0.6
CY(6,5)	94.84	0.5
CY(3,4)	98.52	0.5
CY(4,4)	96.51	0.4
CY(6,7)	98.91	0.3
b'(9,4)	98.96	0.3
b'(16,7)	100.96	0.3
CY(6,4)	92.89	0.2
CY(6,6)	96.84	0.2
b'(9,1)	92.71	0.2
b'(16,3)	92.72	0.2
CY(0,0)	95.86	0.2
b'(9,2)	94.73	0.1
CY(3,3)	96.38	0.1
b'(9,5)	101.18	0.1
b'(16,4)	94.69	0.1
CY(6,8)	101.04	0.1
CY(3,1)	92.31	0.1
CY(4,6)	100.79	0.1
b'(16,6)	98.91	0.1
b'(9,3)	96.81	0.1
CY(3,5)	100.71	0.1
Total CY ($0, v'' = 0,1,2$)		8.8
Total (92.0–101.5 nm)		20.9

[a] Calculated for Voyager 1 conditions using 1.6% CH_4 and a solar zenith angle of 62°.

[b] The contributions from direct photodissociative ionization [*Meier et al.*, 1991] are in parentheses with yields $\phi_{108.5} = 0.184$, $\phi_{96.45} = 0.035$, and $\phi_{95.32} = 0.031$.

Clearly, every N_2 band and NI multiplet must be included in the spectral analysis.

Although Figure 2 shows that the NI production rates are small compared to $c'_4(0)$, the substantial $c'_4(0)$ loss shown in Figure 3 produces a combined NI 95.32 and 96.45 nm intensity (5.4 R) that is nearly as bright as CY(0,1). Calculated NI and N_2 band intensities within one UVS resolution element of CY(0,0) at 95.86 nm (94.3–96.9 nm) total 8.5 R, of which only 0.2 R is (0,0). Previous analyses of UVS sunlit disk spectra yielded 6–10 R for the (0,0) band [*Broadfoot et al.*, 1981; *Strobel and Shemansky*, 1982; *Hall et al.*, 1992], after revising the intensities downward by a factor of 1.6 between 91.2 and 105.0 nm as suggested by *Holberg et al.* [1982, 1991]. The present work therefore indicates that a variety of NI multiplets and N_2 bands were misidentified as the (0,0) band in previous analyses.

Calculated N_2 band intensities near CY(0,1) (98.0–99.0 nm) in Table 3 total 9.4 R, of which 7.6 R are CY(0,1). This result is in agreement with reported (0,1) intensities from the sunlit disk, which are between 5 and 10 R. Because the intensities shown in Table 3 use only sunlight for excitation, a contribution from magnetospheric electron impact [*Strobel et al.*, 1992] may not be required to explain the dayside airglow. However, a supplemental magnetospheric source cannot be ruled out owing to evidence of some darkside EUV emission [*Hall et al.*, 1992], uncertainty in the EUV irradiance, and uncertainty in the UVS calibration for this particular spectral region. It is worth noting that the UVS calibration revision suggested by *Holberg et al.* [1982, 1991] was employed by *Strobel et al.* [1991, 1992] but not by *Hall et al.* [1992] for their spectral analysis (D. E. Shemansky, personal communication, 1999). Lingering calibration issues and the relatively low spectral resolution of the UVS in this narrow spectral region make a detailed fit to the data using the results in Table 3 not illustrative, particularly in light of the impending arrival of Cassini to the Saturnian system.

The Ultraviolet Imaging Spectrograph (UVIS) on Cassini has a spectral resolution of 0.2–0.5 nm [*McClintock et al.*, 1993], which is many times better than the UVS and distinguishes any CY(0,0) intensity at 95.86 nm from NI 95.32 and 96.45 nm. Since the NI multiplets and NII 108.5 nm in Table 3 are produced primarily by direct EUV sunlight, their brightnesses could also be used to measure the contribution of magnetospheric electron excitation to the airglow spectrum. Solar activity during the Cassini tour (2004–2008) is expected to be lower than for Voyager 1 [*Lean*, 1991], so the intensities produced by photoelectrons and photodissociative ionization in Table 3 should be weaker than shown, but their relative distribution should be similar. The brightest dayside intensities can be expected where the solar zenith angle is large so that the production rates peak higher in the atmosphere and the emission is more optically thin to CH_4 and N_2 BH I(2,0).

6. Summary

Results from this work show that the brightest portion of Titan's EUV airglow spectrum observed by the Voyager 1 UVS is more complicated than previously believed. For the photoelectron-excited $c'_4(0)$ state, a multiple-scattering model is employed that quantifies both the redistribution of photons from (0,0) to ($0, v'' > 0$) and losses from predissociation, extinction by CH_4, and absorption of (0,1) by the N_2 BH I(2,0) band. Less than 25% of $c'_4(0)$ production appears in CY($0, v''$), and almost all of this intensity is in (0,1), in disagreement with all previous spectral analyses of UVS data, which inferred a (0,0) to (0,1) ratio close to unity. Using photodissociative ionization of N_2 and photoelectron impact excitation on N_2, it is found that NI multiplets and N_2 bands near (0,0) at 95.86 nm are unresolved by the UVS and combine to produce a nadir intensity that is consistent with that reported for (0,0) from the sunlit disk. Previous analyses of Earth's EUV airglow [*Gentieu et al.*, 1981; *Morrison et al.*, 1990; *Feldman et al.*, 2001] identified the relatively bright NI multiplets at 96.45 and 95.32 nm with CY(0,0) weak or absent between them. Thus, if the UVS calibration revision suggested by *Holberg et al.* [1982, 1991] is adopted, it appears that the (0,0) band was misidentified in Titan's dayside airglow. UVIS on Cassini can unambiguously distinguish the NI multiplets at 96.45 and 95.32 nm from any (0,0) intensity, thereby testing this proposed solution to a longstanding puzzle in the UVS Titan airglow data.

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